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Enhancement of Preoxygenation for Decompression Sickness Protection: Effect of Exercise Duration

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Introduction: Since strenuous exercise for 10 min during preoxygenation was shown to provide better protection from decompression sickness (DCS) incidence than resting preoxygenation, a logical question was: would a longer period of strenuous exercise improve protection even further? **Hypothesis:** Increased strenuous exercise duration during preoxygenation increases DCS protection. **Methods:** There were 60 subjects, 30 men and 30 women, who were exposed to 9144 m (4.3 psia) for 4 h while performing mild, upper body exercise. Before the exposures, each subject performed three preoxygenation profiles on different days in balanced order: a 90-min resting preoxygenation control; a 240-min resting preoxygenation control; and a 90-min preoxygenation including exercise during the first 15 min. The subjects were monitored at altitude for venous gas emboli (VGE) with an echo-imaging system and observed for signs and symptoms of DCS. **Results:** There were no significant differences in occurrence of DCS following any of the three preoxygenation procedures. Results were also comparable to an earlier report of 42% DCS with a 60-min preoxygenation including a 10-min exercise. There was no difference between VGE incidence in the comparison of protection offered by a 90-min preoxygenation with or without 15 min of strenuous exercise. The DCS incidence following a 240-min resting preoxygenation, 40%, was higher than observed during NASA studies and nearly identical with the earlier 42% DCS after a 60-min preoxygenation including exercise during the first 10 min. **Conclusion:** The protection offered by a 10 min exercise in a 60-min preoxygenation was not increased with extension of the preoxygenation exercise period to 15 min in a 90-min preoxygenation, indicating an upper time limit to the beneficial effects of strenuous exercise.

Keywords: altitude, DCS, VGE, emboli, decompression sickness, exercise, denitrogenation, preoxygenation, prebreathe.

A POTENTIAL EXISTS for development of decompression sickness (DCS) following decompressions from 14.7 psia (sea-level pressure) to 4.3 psia (30,000 ft). Extravehicular activity (EVA) for International Space Station (ISS) construction and maintenance will involve over 400 such decompressions between 2001 and 2010. Although a 2987-m (10.2-psia) staged decompression was used successfully in preventing DCS during EVA from the Space Shuttle, that procedure is not possible during EVA from the ISS because it maintains a constant 14.7-psia, sea-level environment. Reverting to the previously used 4-h preoxygenation (prebreathe) is very inefficient and costly due to the inherent crew fatigue that limits subsequent EVA duration. An increase in the efficiency of denitrogenation has been accomplished by including brief, strenuous exercise during the preoxygenation to increase ventilation and tissue perfusion (24). Exercise during preoxygenation is

now in use to reduce DCS risk for U-2 high altitude reconnaissance missions (8). Strenuous exercise for 10 min was also incorporated into a reduced-preoxygenation procedure prior to EVA from the ISS beginning with STS-104 in mid-2001 (Gernhardt M. Personal communication; 2001) to reduce total preoxygenation time.

The current study was based on the success with incorporating 10 min of exercise at 75% of VO_{2peak} during a 60-min preoxygenation prior to exposures simulating EVA (24). We hypothesized that there would be a further increase in protection from extension of the exercise period from 10 min to 15 min and the total preoxygenation from 60 to 90 min.

METHODS

The protocol was reviewed and approved by the Brooks AFB Institutional Review Board. The voluntary, fully informed consent of the 30 male and 30 female subjects (Table I) used in this research was obtained in accordance with AFI 40-402 (Protection of Human Subjects in Biomedical and Behavioral Research). All subjects passed an appropriate physical examination and were representative of the USAF rated aircrew. They were not allowed to participate in SCUBA diving, hyperbaric exposures, or flying for at least 72 h before each scheduled altitude exposure. VO_{2peak} was determined with a SensorMedics® 2900z (Yorba Linda, CA) metabolic measurement system as each subject performed dual-cycle ergometry (24) (2-min stages) to a mean RQ of 1.1 and American College of Sports Medicine test termination guidelines (1). Body fat was measured using a three-site caliper method (1). Subject data in Table I are based on averages for all three exposures except

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TABLE I. SUBJECT ANTHROPOMETRICS; MEAN \pm SD (30 MALE AND 30 FEMALE SUBJECTS).*

Gender	Age (yr)	Height (cm)	Weight (kg)	Body Fat (%)	BMI (wt/ht, kg \cdot m ⁻²)	VO _{2peak} , (ml \cdot kg ⁻¹ \cdot min ⁻¹)
Males	30.2 \pm 5.4	179.1 \pm 6.2	82.1 \pm 10.2	17.3 \pm 5.5	25.6 \pm 2.7	42.0 \pm 6.6
Females	29.8 \pm 5.7	163.6 \pm 5.6	62.1 \pm 7.4	22.5 \pm 4.6	23.2 \pm 2.3	35.9 \pm 5.7
Both	30.0 \pm 5.5	171.3 \pm 9.9	72.1 \pm 13.4	19.9 \pm 5.7	24.4 \pm 2.7	38.9 \pm 6.8
Control†	29.4 \pm 5.5	177.7 \pm 7.9	84.0 \pm 10.8	21.7 \pm 4.5	26.5 \pm 2.4	41.5 \pm 6.0

* Body fat only available for 29 males and 29 females.

† From Webb et al. (24); Body fat only available for 17 of the 26 males.

for VO_{2peak}, which was determined prior to the first exposure.

Prior to each 4-h altitude exposure, a physician conducted a short physical examination of subjects to identify any signs of illness or other problem that would endanger the subject or bias the experimental results. An ear and sinus check to 1524 m (5000 ft) was accomplished prior to each exposure.

A neck-seal respirator made by Intertechnique® (Plaisir Cedex, France) was used to deliver oxygen. This mask provided a slight positive pressure (2 cm of water) that reduced the opportunity for inboard leaks of nitrogen from the atmosphere and was more comfortable than the standard aviator's mask. Breathing gas during preoxygenation and while decompressed was 100% oxygen (aviator's breathing oxygen; normal analysis 99.7–99.8% oxygen).

The exercise during preoxygenation employed a dual-cycle ergometer (25) operated at 50 rpm. The exercise began with a 2-min, legs-only warm up and the remaining 13 min of the dual-cycle ergometry (arms and legs) was at 75% of peak oxygen uptake (VO_{2peak}). This ex-

tended the period at 70–75% of VO_{2peak} from 8 min during the previous study (10-min exercise including a 2-min warmup) (24) to 13 min. The 75 min of resting preoxygenation following the exercise, as well as the 90- and 240-min resting preoxygenations prior to both control exposures (Table II), were accomplished while supine on a gurney with a headrest. Order of the three exposures was balanced to control for order effects.

At 16-min intervals, the subjects were monitored for VGE using a Hewlett Packard Sonos 1000 Doppler/Echo-Imaging System. This system permits both audio and visual monitoring and recording of gas emboli in all four chambers of the heart and allows for easier and more accurate determination of emboli presence than Doppler alone. Indeed, the use of echo-imaging has allowed visualization of VGE incidence at least as high as reported during identical exposures at NASA-Johnson Space Center to 4.3 psia following a 4-h preoxygenation; 46% VGE (23) vs. 55% VGE in this study. Detection of any left ventricular gas emboli (LVGE) was made possible due to these echo-imaging sessions and was cause for immediate recompression to avoid potential serious symptoms re-

TABLE II. PREOXYGENATION CONDITIONS AND RESULTS (MEANS) AT THE COMPLETION OF 4-h, 9144-m (30,000-ft) EXPOSURES WITH MILD EXERCISE.

Preoxygenation min Exercise (E) min Rest (R)	Subject Group	% VGE	% Gr4 VGE	% DCS
90R	Males (N = 30)	90.0	46.7	66.7
90R	Females (N = 30)	66.7	26.7	53.3
90R	Both (N = 60)	78.3	36.7	60.0
15E/75R	Males (N = 30)	76.7	36.7	53.3
15E/75R	Females (N = 30)	66.7	16.7	53.3
15E/75R	Both (N = 60)	71.7	26.7	53.3
240R	Males (N = 30)	66.7	26.7	46.7
240R	Females (N = 30)	43.3	10.0	33.3
240R	Both (N = 60)	55.0	18.3	40.0
60R*	Males (N = 26)	80.8	46.2	76.9
10E/50R*	Males (N = 26)	80.8	42.3	42.3
10E/5R*	Males (N = 22)	81.8	50.0	63.6
10E/24ALE/116AR†	Both (N = 45)	31.0	6.7	0.0
10E/50AR‡	Males (N = 39)	51.3	23.1	43.6
10E/50AR‡	Females (N = 10)	60.0	20.0	30.0
10E/50AR‡	Both (N = 49)	53.1	22.4	40.1

* From Webb et al. (24) and AFRL DCS Database; R = adynamic resting preoxygenation; dynamic exposure.

† From Vann et al. (22); subdivision of results by gender not available; ALE = adynamic light exercise during preoxygenation; AR = adynamic resting preoxygenation; adynamic exposure.

‡ From Balldin et al. (2); AR = adynamic resting preoxygenation; adynamic exposure.

sulting from arterial gas emboli. VGE were graded using a modified Spencer Scale (18).

The primary purpose for VGE monitoring, other than safety, is the strong relationship between level of VGE and exposure severity. Although the population response shows increased VGE incidence with increased altitude (28), a large percentage of exposures present with VGE and no symptoms: 28.3% of 2696 subject-exposures in the U.S. Air Force Research Laboratory Hypobaric DCS Database; and 24.5% of 1322 exposures reported by Conkin et al. (5). These data cast doubt on the DCS predictive value of VGE for any individual. Also, in 221 of the 1076 subject-exposures with DCS (20.5%), no VGE were observed (U.S. Air Force Research Laboratory DCS Database). However, the relationship between VGE and DCS becomes of particular interest when exercise is performed before or during exposure due to concern that exercise, even before exposure, elicits VGE and DCS (4).

During exposure, subjects performed three upper-body "EVA" exercises as described in Webb et al. (24). The subjects walked less than 10 steps between exercise stations and the echo-imaging station at 4-min intervals. Minimum time between exposures was at least 72 h and averaged 59 d.

Exposures were terminated according to the following criteria: 1) completion of the 4-h scheduled exposure; 2) development of any signs or symptoms of DCS; 3) detection of LVGE. Normally, every subject accomplished a 2-h postbreathe with 100% oxygen after recompression to ground level.

Log Rank and Wilcoxon's tests were used to compare homogeneity of DCS and VGE vs. time following the three preoxygenation profiles. A Chi-square test was used to compare these results with previous data from this laboratory obtained in the same altitude chamber using virtually identical procedures.

Since fatigue associated with exercise might be a concern, we compared the level of fatigue produced by the 1.5-h exercise-enhanced preoxygenation procedure with the 1.5-h resting preoxygenation procedure. A performance assessment battery (PAB) was used that has been used to measure fatigue during a Space Shuttle mission (7). The PAB consisted of a critical tracking task with mouse-driven input from the subject. Subjects were trained to their own consistent level of performance and received refresher training within 3 d before each exposure. The mean and maximum λ , and the mean and highest degree of cursor instability controllable by the subject during each 2-min test period were used as the metric of performance. Since fatigue was the desired variable to be measured by this test, the metrics from tests before preoxygenation, at the end of each hour of the 4-h exposure, and 15–30 min after recompression to ground level were recorded. To ensure that fatigue due to exercise or rest during preoxygenation was the major variable, the only subject data used were from the 19 subjects who completed exposures after both 90-min preoxygenations without developing symptoms. The results from the tests were plotted, a linear regression (MS Excel trendline) applied to determine any trend in level of performance, and overall

means of maximum λ were compared between preoxygenation profiles.

RESULTS

There were no observations of LVGE during any of the exposures. Table II shows the results from the 4.3-psia exposures following the three preoxygenation conditions (breathing 100% oxygen): 240 min at rest (240R); 90 min at rest (90R); and 90 min including 15 min of exercise followed by 75 min at rest (15E/75R). Since the subjects served as their own controls, male and female exposure results were combined for the DCS and VGE onset curves. Comparisons of results showed no significant differences ($p > 0.1$) between DCS, Grade 4 VGE, or VGE (Fig. 1) between the exposures following 90 min of preoxygenation with or without exercise enhancement. There were significantly higher final incidences ($p < 0.02$) of DCS, Grade 4 VGE, and VGE following 90R than following 240R. The only significant difference between 15E/75R and 240R was higher VGE following the 15E/75R ($p < 0.01$).

A subdivision of symptom categories and latencies is shown in Table III. This table shows all symptoms observed during the 180 subject-exposures. The total number of symptoms includes multiple symptoms observed during 18 subject-exposures; hence, the total is larger than the number of subject-exposures with symptoms shown in Table II. Three subject-exposures resulted in symptoms requiring hyperbaric oxygen therapy (HBO) for resolution; two in the 90R profile and one in the 15E/75R profile.

The male and female exposures were separated into upper and lower halves based on the various anthropometric variables to determine their influence on DCS incidence. No effect was shown with lower vs. higher body fat, weight, or height. However, male subjects with a lower body mass index (BMI; [weight in kg]/[height in m]²; mean BMI of 23.4 vs. 27.8; 44% DCS vs. 67%; $\chi^2 = 4.5$) had a significantly lower level of DCS as did all exposures with a lower BMI (mean BMI of 22.5 vs. 26.4; 43.3% DCS vs. 58.9% DCS; $\chi^2 = 4.4$). Females did not show such a relationship. The younger half of male subjects had significantly less DCS (mean age 25.7 yr; 44% DCS) than the older males (mean age 34.7 yr; 67% DCS; $\chi^2 = 4.5$). Gender was not a significant factor in symptom development between the 90 exposures of 30 men (55.6% DCS) vs. 90 exposures of 30 women (46.7% DCS) ($\chi^2 = 1.4$). Although the relatively small sample size may have precluded detection of a difference, the results are in agreement with other gender comparisons from this laboratory (26).

The slopes of the regression lines over the 6-h period of PAB testing were less than 0.46 with mean λ (a measure of test difficulty level achieved) of 3.74 for the resting and 3.75 for the exercising group. A comparison of the 19 subjects who completed the 4-h exposures following both 1.5-h preoxygenation procedures showed mean maximum λ of 4.87 and 4.76, respectively, for the resting and exercising groups. A comparison of mean maximum λ from the first three PAB sessions vs. the last three sessions indicated slight improvement in the latter tests with a 6.0% (n.s.) increase following the exercise-enhanced

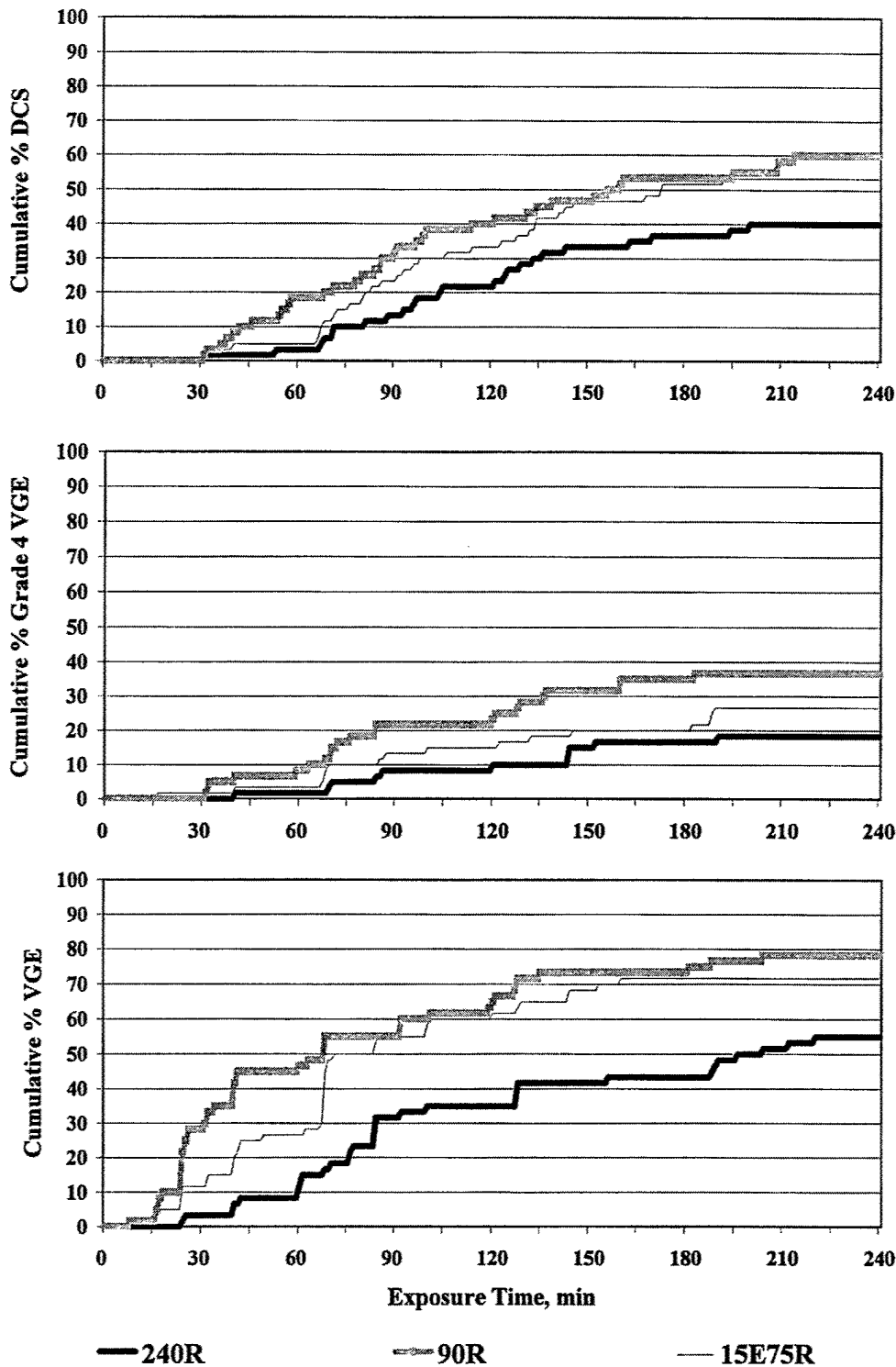


Fig. 1. Cumulative DCS, Grade 4 VGE, and VGE incidence during 4-h, 9144-m (30,000-ft) exposures with mild, dynamic exercise ($n = 60$; 30 males, 30 females).

preoxygenation and a 3.9% increase following the resting preoxygenation. These data indicate that level of fatigue, as measured by this PAB, did not change throughout exposure following either 1.5-h preoxygenation procedure.

DISCUSSION

The 90-min and 240-min resting preoxygenations during this effort produced less DCS than the earlier 60-min resting preoxygenation (Table II). When resting

preoxygenation time is plotted vs. DCS incidence, the three values show an expected trend of increased DCS protection with more preoxygenation time (27). The consistency of our observed decrease in DCS with increasing, resting preoxygenation is an indication that the DCS susceptibilities of the study's subject pools to symptom development were not a major factor in determining the effectiveness of resting preoxygenation. The lack of substantial difference between anthropometric data on the males in the current study as com-

TABLE III. SYMPTOMS CATEGORIES AND MEAN ONSET TIMES.

Symptom Description	Profiles*		
	90R # (Onset) [†]	15E/75R # (Onset) [†]	240R # (Onset) [†]
Pain	43 (113)	36 (108)	24 (114)
Paresthesia	10 (123)	7 (116)	5 (76)
Skin mottling	1 (100)	1 (98)	0
Neurologic	1 (209)	5 (98)	1 (69)
Pulmonary	3 (160)	1 (143)	0

* 90R = 90 min of resting preoxygenation; 15E/75R = 15 min of exercising preoxygenation plus 75 min of resting preoxygenation; 240R = 240 min of resting preoxygenation.

[†] Number of symptoms observed; (mean onset time of symptom category, min).

Note: Includes multiple symptoms observed during 18 subject-exposures.

pared with males in the earlier study, particularly the subjects' VO_{2peak} , further supports similarity of the two subject groups so that the data could be used in comparing DCS and VGE incidence based on procedural differences rather than differences in subject populations (Table I). The finding of age as a DCS risk factor in males is consistent with another report from this laboratory (19).

There was no significant difference in the male DCS incidence following 15E/75R (53.3% DCS) compared with results of an earlier report (24) using a 10-min exercise-enhanced, 60-min (10E/50R) total preoxygenation. Failure of the protocol tested here to reduce DCS incidence below that with 10E/50R was unexpected and difficult to explain. The first 10 min of both preoxygenation procedures were identical and should have produced the same level of denitrogenation up to that time. Several possible mechanisms, perhaps in combination, may explain why 5 min of additional exercise at 75% of VO_{2peak} did not increase the effectiveness of denitrogenation during the ensuing 75-min preoxygenation.

One difference between the experiments is a slight (less than 1°C) exercise-induced increase in core temperature resulting from 5 additional min of strenuous exercise (15). An increase in core temperature has been shown to be associated with a reduction in tendon blood flow (21). Reduced tendon blood flow could, in turn, slow the rate of denitrogenation in the critical tissues, resulting in the lack of improved DCS protection.

Another difference could be increased plasma fluid shift to extravascular muscle tissue which arises from increased capillary pressure due to increased cardiac output during exercise (6,11,14,16,17). The 13-min exercise may have resulted in more fluid shift than the 8-min exercise at 70–75% of VO_{2peak} , yielding additional muscle tightness which could remain up to 45 min after exercise has stopped (14). Additional muscle tightness could potentially inhibit tendon blood flow, hence denitrogenation. Redistribution of blood flow to active muscle producing a decreased ratio of blood flow in tendon to muscle during submaximal exercise (20) may also result in reduced tendon denitrogenation. It is gen-

erally accepted that DCS joint pain originates in the "slow" denitrogenating tissues around the joints with relatively low blood flow, e.g., tendons. Joint pain symptoms accounted for 21 of the 22 symptoms (95%) observed following 13 min of exercise at 75% of VO_{2peak} vs. 10 of 17 symptoms (59%) following the 8 min at 75% of VO_{2peak} ($p < 0.05$), while VGE showed no corresponding relationship (Table II). The combined effect of these physiologic mechanisms (increase in core temperature, fluid shifts, and redistribution of blood flow) may explain the lack of improvement in DCS protection resulting from the longer-duration, exercise-enhanced preoxygenation procedure.

The data from the 90-min preoxygenations with and without 15 min of strenuous exercise indicate that 15 min of strenuous exercise at the beginning of a 90-min preoxygenation is of no significant value in reducing DCS. The results also clearly show that the strenuous exercise 75–90 min prior to exposure does not increase incidence or severity of VGE. This finding is counter to the speculation that strenuous exercise causes formation of microbubbles (4) which, during decompression, result in increased VGE and DCS. Vann et al. (22) described results that indicated 10 min of strenuous exercise during a 120-min preoxygenation was very effective in reducing DCS under adynamic exposure conditions, not walking or standing during preoxygenation or exposure. However, Balldin et al. (2) have reported that there appears to be no difference between adynamic and dynamic (walking) exposure. Pilmanis et al. (13) found no difference in DCS incidence between dynamic and isometric arm (or leg) exercise during 4-h exposures at 8992 m (29,500 ft). Although we believe that microbubbles are probably formed during the strenuous exercise during preoxygenation by the process of tribonucleation (9), the lack of any difference in DCS and VGE implies that such microbubbles have a life history which does not impact DCS and detectable VGE.

One potential fate of an increased number of intravascular microbubbles prior to decompression is sequestration in the lung prior to or during decompression (3), effectively enhancing the rate of denitrogenation by providing a transport mechanism independent of solubility in blood. This concept has been demonstrated in the hyperbaric environment by Kindwall et al. (10), who reported enhanced nitrogen elimination at 50 fsw resulted from intravascular bubble formation, greatly increasing transport capacity for given partial pressures of nitrogen in the blood. Growth of an increased number of microbubbles in extravascular tissues during decompression should yield a smaller final bubble size due to the smaller quantity of dissolved nitrogen available to each bubble. The smaller quantity of nitrogen available is a result of closer proximity to other bubbles which compete for nitrogen during the decompression-induced growth process (12).

Previous speculation has implicated exercise prior to decompression as a causative factor in the production of gas microbubbles and increased DCS incidence during exposure (4). Tribonucleation as it occurs on curved surfaces (9) could explain increased numbers of extravascular microbubbles following exercise at altitude. Countering this effect, physical activity during preoxy-

generation should increase the rate of diffusion of nitrogen from a relatively high extravascular concentration to a nearly zero intravascular concentration. Denitrogenation is effected by movement of gas emboli from the tissue capillaries to the lung where they are sequestered and their nitrogen expired (3). This process could combine with increased diffusion of nitrogen from the tissues to result in greatly enhanced DCS protection even with formation of more VGE.

Grade 4 VGE, as the highest grade of VGE, is considered by some to be an indicator of severe decompression stress (22). As seen in Table II, Grade 4 VGE are not at higher levels following exercise-enhanced preoxygenation than following an equal period of resting preoxygenation. Indeed, the level of Grade 4 VGE following 10E/5R (only males) is within 4% of the Grade 4 VGE in males following 90R. The lack of a significantly elevated incidence of Grade 4 VGE following preoxygenations including strenuous exercise implies that this stress indicator is apparently not affected by exercise within as little as 5 min of decompression. The lack of additional VGE risk due to strenuous exercise is supported by the DCS results following preoxygenations including strenuous exercise vs. those following resting preoxygenations (Table II) and the findings during NASA-sponsored testing with mild vs. strenuous exercise (22).

CONCLUSIONS

The results of this study show that 15 min of strenuous exercise at the beginning of a 90-min preoxygenation did not decrease or increase the incidence of either DCS or VGE relative to resting control preoxygenations of 90 or 240 min. The 40% DCS risk following a 240-min resting preoxygenation was nearly identical with the 42% DCS observed after only 60 min of preoxygenation beginning with 10 min of strenuous exercise (24). The protection offered by that 10-min strenuous exercise was not improved with extension of the preoxygenation exercise period to 15 min, indicating an upper time limit to the beneficial effects of continuous, strenuous exercise during preoxygenation.

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